# MICRO-SENSOR NETWORKS

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## ABSTRACT

The concept of an all-fiber, 1~-based sensor network is presented. Fundamental issues including topology tradeoffs, power budget, and power distribution subsystem arc analyzed. Some potential applications of such sensor networks arc discussed.

## INTRODUCTION

Each year, the airline industry spends billions of dollars on structure condition tests. The same test is normally required to be repeated several times during the lifetime of an airplane, and the frequency of the test is normally required to be increased as the. airplane. gets older, but still some structures fail before the next scheduled test is performed. Many of these tests can not detect internal degradation/damage in the structure, because normally only the surface of the structure is available for a test. These problems arc also shared by users of many other large structures such as bridges, buildings, ships, and spacecraft, pipelines, . . . etc. In spare and under the sea, performing such tests can be also very expensi ve or near] y impossible,. As a result, there is a need for a built-in, real-lime, structure monitoring system that can constantly monitor the condition of both inside and outside of a structure and issue a real-time warning as a test result indicates the monitored structure is about to fail.

A network of sensors distributed over the strategic locations in a structure is one of the solutions to the structure monitoring problem. To reliably and accurately detect a potential structure failure, multiple sensor types may be needed. For example, strain gauges may provide a history of the net force exerted ou various points in the Structure., chemical sensors may provide. information about corrosion by sensing the chemical released during the corrosion process. By comparing the results with the mechanical limit and chemical properties of the structure, and correlating these two different data sets, the safely status of the structure can be more accurately determined. To cover all the strategic points in a large structure, thousands of sensors and wires may be needed. It is advantageous to integrate all the sensor types together at a given point and transmit all the sensor data through the same transmitter. The sensor network should also be fault-tolerant to reduce the need for maintenance, because in some, applications the. sensor network may be cmbcddcd in the structure and is inaccessible to service. in some environments, the network should also be immune to corrosion and electromagnetic interference (EM 1) and in some. other environments, the network may be required not 10 generate 1 EM fields that could interfere with other EM I-sensitive devices. 1 lence, how to *reliably* and *compactly* network the Sensor nodes together become two very important issue.s in designing the sensor net work.

## MICRO-SENSOR NETWORKS

In this paper, wc investigate a unique class of sensor networks that arc potentially reliable and compact.[1-3] This is an all-fiber sensor network in which both power and sensor data arc transmitted through fibers. Because fibers are used, tbc network is 1 EMI-immune, corrosion-resistive, and not susceptible to the problems of ground-potential differences. in addition, the network is much more compact and light-weight than its copper-wire Counterpart. In large structures, an all-fiber network also extends over a longer distance without a repeater.

The potential disadvantages of an all-fiber sensor network arc higher cost, and lower power deliverable to sensor nodes. The cost may gradually be brought down by the fast-growing market of other fiber and laser-based products such as Cable TV and 0)-ROM systems. The low power available limits the bandwidth of data transmission. 1 Iowever, in many sensor systems, because the bandwidth requirement is very low, the low power limitation may not be a problem, in gene.ral. For a system "that consumes higher power on the nodes, the number of fibers can be increased to deliver more power to each node. But, in general, a low-power sensor node design is essential to the implementation of an all-fiber sensor network. From a comparison with the performance on a batlery-powered watch, which can run for a couple years without changing battery, we estimate, that a low-power sensor node should be very feasible. In general, a low-power design also leads to a compact device, which is a valuable properly to the sensor network.

Figure 1 shows the key elements in an all-fiber sensor network. The base station consists of a laser source for powering up the sensor nodes, and a computer that performs network management, data analysis, and status reporting. The sensor arrays can be networked over several fibers. A sensor node consists of one or more sensors and an IC chip that digitizes sensor signals and transmits them back to tbc base station. It is also possible to integrate a certain semiconductor-based sensors into the IC chip, forming an extremely compact micro-sensor chip. Although only onc line is drawn for each branch, there can be more than onc fiber going through each branch to provide separate power and data paths. If the base, station is far away from the user, a separate data link can be installed between the base station and the user. Or in the case of aircraft monitoring system, the massive data of the base station can be collectively downloaded to a central station during the ground time..

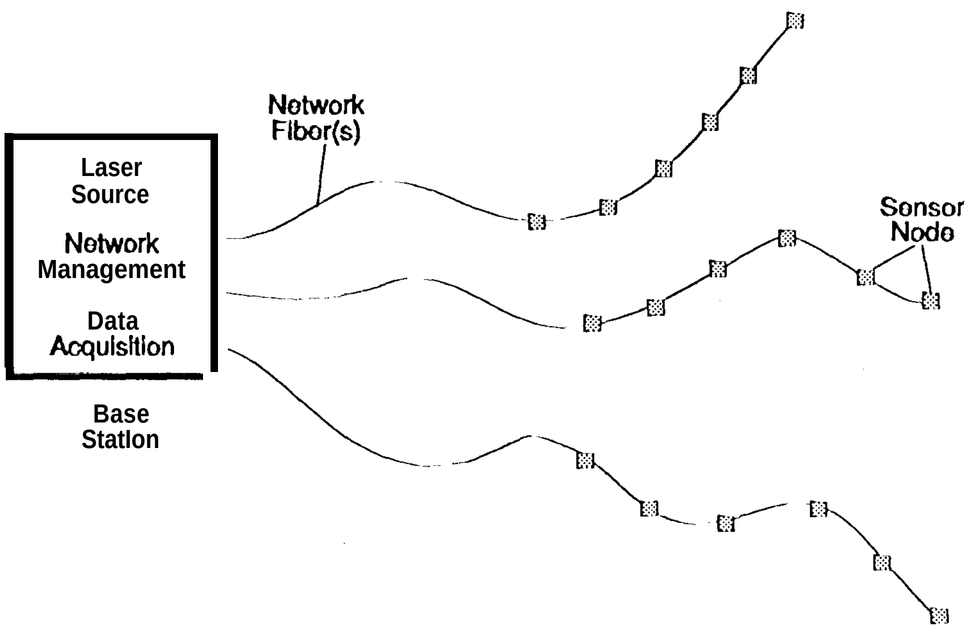


Figure 1 Distributed sensor network

## APPLICATIONS

Several potential applications of a sensor network arc described in this section, Some of them can be implemented cost-effectively and adequately by usc of copper wires, while those requiring EMI-immunity and corrosion-resistance will benefit exclusively from an all-fiber sensor network. Despite the cost factor, which could change dramat i call y by the end of this decade, an all-fiber sensor network is more reliable., more compact and thus more appealing than the copper-wire network, in general. Hence, usc of a low-cost all-fiber sensor network for applications described Mow may become a reality some day.

Structures A sensor network could be embedded in a strut.turc, to monitor structural parameters where these were of concern,

- strain and corrosion monitoring in aircraft components
- shape control in flexible structures
- strain monitoring in architectural structures

These applications could lead to improved performance of flexible structures such as aircraft wings. Better knowledge of the status of rigid structures, such as bridges and old buildings would also be possible. A fiber based system would preserve the non-conductive properties of a composite wing, which could be important for both the network and the wing. A fiber system would remain undamaged in the event a monitored structure were struck by lightning.

**Power Systems** In power system applications, the problems of ground potential differences can justify the use of a fiber-based network. Data acquisition in the power system, and some industries, also requires immunity to EMI and harsh chemicals, making fiber the ideal choice. Some examples are,

- data acquisition in a substation or generating station
- stress, strain and temperature monitoring of pipes and headers in a generating station
- leak detection in pipes and cables
- hot-spot monitoring of large devices

Other power system applications, that take advantage of the insulating nature of the fiber to measure parameters at high voltage are also possible. Here the fact that the sensor is remotely-powered is also important, as the inaccessible nature of the sensor makes low maintenance essential. Some examples are,

- line temperature monitoring
- line vibration monitoring
- disconnect position monitoring
- fuse status monitoring

**Non-fiber Power** Inside buildings, the network could have a variety of monitoring and control uses,

- more effective HVAC control
- building automation
- security systems

Based on the users, the applications mentioned above and some new ones can be classified as in Table 1.

**TABLE 1 Applications of Micro-Sensor Networks**

| INDUSTRY | INSTITUTE/SPACE |
|---|---|
| **Civil Infrastructure**<br>(Bridges, Buildings)<br>Structure Alignment | **Antenna Surface**<br>(Shape Distortion) |
| **Commercial and Military Aircraft**<br>(Health Management)<br>EMI, Cable Size&Weight . . . | **Spacecraft Structure**<br>(Vibrations, Micro Meteorites, Surface Contamination, Charge Effects, Temperature) |
| **Pipeline**<br>(Corrosion Leakage, Valves) | **Seismic Array** |
| **Heavy Equipment**<br>(Ventilation, Compressor) | **Space Station** |
| **Power Industry**<br>(Substation, Generating Station, HV Line) | **Smart Highway**<br>(Ice, Cracks, Oil, Flatness) |

The readers can probably add more applications to this list,

## BASIC FUNCTIONS OF MICRO-SENSOR CHIP

Figure 2 shows the basic functions of a micro-sensor chip. A number of control protocols are possible. In one, when the micro-sensor chip receives a command from the base station to perform a measurement, the microprocessor compares the node address attached to the command and issue a control signal to acquire. a set of sensor data if the addresses match. The sensor data, if consisting of multiple sensor' types, will be first multiplexed and them sent to the analog-to-digital (A/D) converter. The A/D converter digitizes the signals and passes them to the micro processor and then to the LED or the laser driver to transmit the data back to the base station, Under this configuration, the addressing has to be performed through the power port. Another possible configuration not shown is to have an additional port and receiver for addressing.

An alternative to the LED or laser is an optical modulator which consumes much less power than the LED or laser. The optical beam needed in the modulator approach can be either from tapping some optical power from the power distribution fiber or from a separate fiber powered by a separate. laser source., In the former approach, the power consumption is probably not too much less than the LED or laser approach, because the insertion loss of a modulator is fairly large. in the latter approach, power is not extracted from the power distribution fiber. So, more power can be available for the micro-sensor chip. However, there is a limitation to this approach as discussed below.

The insertion loss of a modulators can be lower than 1 5%, if it is polarization-sensitive. This estimate is based on a coupling efficiency of SO% per facet of the modulator, and a loss of 50% due to the Polarization-sensitivity. As an example, if there are ten nodes, the total insertion loss of the modulators is an extremely large 90 dB ! For polarization-insensitive modulators, the total insertion loss is still 60 dB, which is almost within the capability of today's transmitter and receiver.

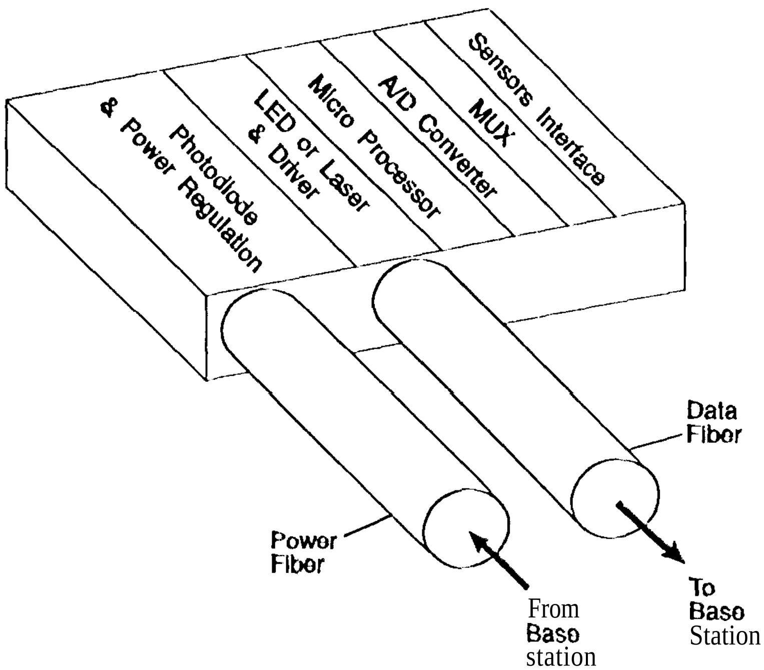


Figure 2 Functional diagram of a micro-sensor chip

## NETWORK TOPOLOGIES

One feature of a sensor network that is different from a computer network is that the sensor nodes do not need to talk to each other. Only the base station of the sensor network needs to talk to a sensor node. This happens when the base station needs the sensor nodes to send data back to the. base station. This implies that as far as the addressing scheme is concerned, what topology to use dots not matter too much. Topology becomes more critical when power distribution, data transmitting, and fault tolerance are concerned. In the following, we will discuss the properties of different topologies and their tradeoffs.

There are at least three topologies that can be considered for sensor networks as shown in Figure 3. The first one is a star topology in which each node is connected to the base station directly. The second one is a daisy chain topology in which all the nodes arc chained together. The third one is a hybrid topology which is a mixture of star and daisy chain. The data transmission may usc a different topology from the power distribution. In the hybrid topology, power distribution and data transmission may have different number of nodes per branch, determined by their own power budget.

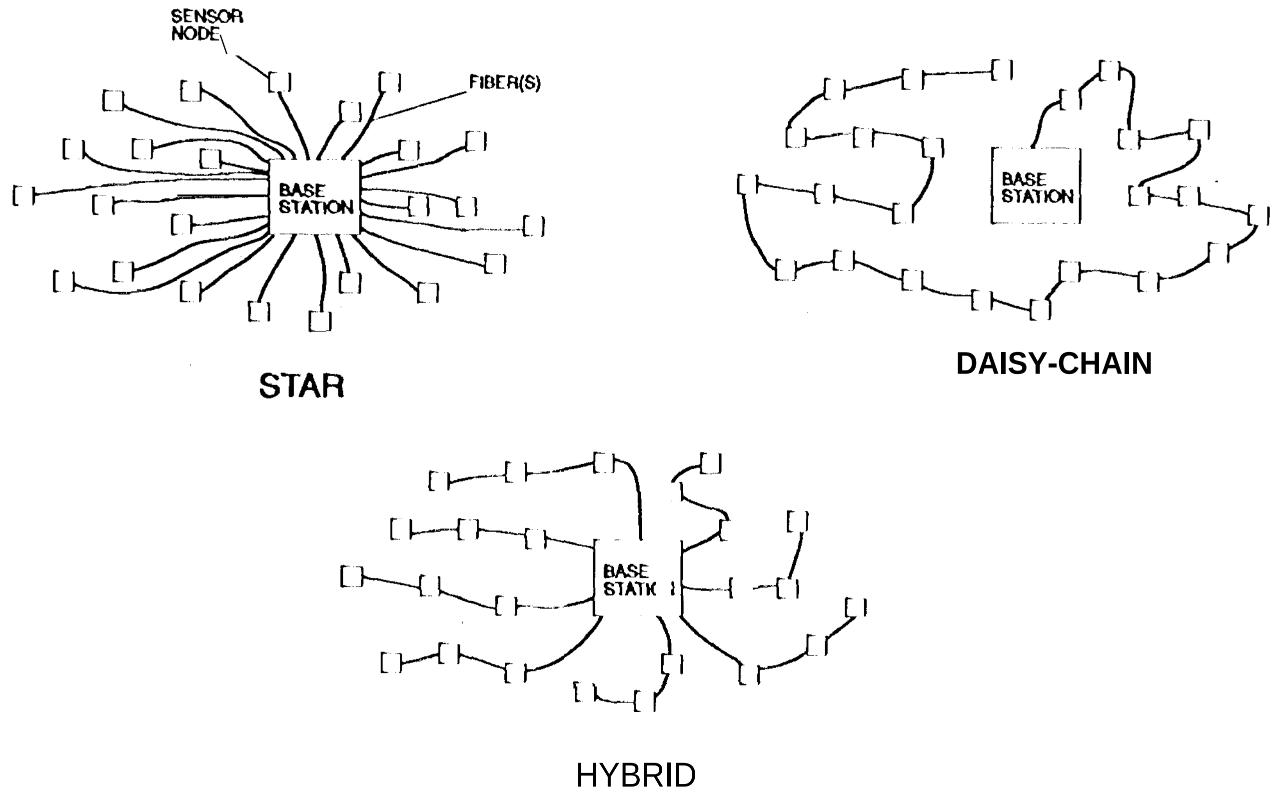


Figure 3 Sensor network topologies. The line may represent power distribution fiber or data transmission fiber.

'1'able, 2 lists the tradeoffs of these topologies. The number that follows each property in the first column, based on our personal tuition, is the weight representing the relative importance of that property with respective to others. The scale of the weight is 1 to 4 with 4 being the most important. The number that follows the. grade of a topology is the relative score of a topology for a properly, again somewhat subjectively estimated. The range of the score is from 1 to 3. 3 is given to the most favored topology for a properly. The weighted total score is calculated as the inner product of the weight column and the score column. It can be used as a general index for selecting the most suitable topology.

From 'J'able 2, star topology has the highest score, closely followed by the hybrid topology. The daisy-chain topology is the distant last, The only two properties that daisy-chain topology has the highest score is the NUMBER OF FIBERS NEEDED and LABELING AND INSTALLATION. The only property that a hybrid topology has the highest score is the MAXIMUM NUMBER OF NODES. Thus, the only way these two topologies can get a higher score than star topology is by increasing the weights of these two properties to be much higher than the current scale of 1 to 4. This is not unreasonable, because the scale of property may be applicat ion dependent.

Because the diameter of fibers arc fairly small, it is possible to package all the fibers in a single cable with a diameter slightly larger than that of a sing]c-fiber cable to increase the score of handling and installation for star topology. This possibility is discussed below.

TABLE 2 Topology Tradeoffs

| PROPERTY/WEIGHT | STAR | DAISY-CHAIN | HYBRID |
|---|---|---|---|
| NUMBER OF FIBERS NEEDED/4 | High/1 | Low/3 | Medium/2 |
| FAULT TOLERANCE/3 | High/3 | Low/1 | Medium/2 |
| HANDLING AND INSTALLATION/4 | Complicated/1 | Simple/3 | Medium/2 |
| ADDRESSING/CONTROL/2 | Simple/3 | Complicated/1 | Medium/2 |
| OPTIONAL PARALLEL ADDRESSING/CONTROL/1 | Yes/3 | No/1 | Yes (branch)/No(node)/2 |
| POWER DISTRIBUTION DESIGN/4 | Simple/3 | Complicated/1 | Medium/2 |
| MAX. POWER AVAILABLE/4 | High/3 | Low/1 | Medium/2 |
| DATA LINK DESIGN/4 | Simple/3 | Complicated/1 | Medium/2 |
| OVERALL DATA RATE/2 | High/3 | Low/1 | Medium/2 |
| MAXIMUM NUMBER OF NODES/4 | Medium/2 | Small/1 | Large/3 |
| COST PER NODE (POWER DISTR.)/4 | Medium/2 | High/1 | Medium/2 |
| COST PER NODE (DATA LINK)/4 | Medium/2 | High/1 | Medium/2 |
| **WEIGHTED TOTAL SCORE*** | 92 | 56 | 84 |

* SCALE OF WEIGHT: 1 ~ 4; SCALE OF TOPOLOGY SCORE: 1-3
WEIGHTED TOTAL SCORE = COL.(PROPERTY WEIGHT)•COL.(TOPOLOGY SCORE)

## A SINGLE-CABLE IMPLEMENTATION OF STAR TOPOLOGY

A special implementation of star topology, that can increase the total score of star topology in 'Table. 2., is to package all the fibers into one cable. By doing so, there will be less chance to tangle the fibers and the node.-labeling will also be easier. This implementation can be used with the hybrid topology 100 by packaging all the branches into one cable.

Figure 4 shows two single-cable implementations of star topology. In Fig. 4(a), star topology is used for both power distribution and data transmission. The addressing is performed through the power distribution fiber. in Fig. 4(b), star topology is used for data transmission, while daisy-chain topology is used for power distribution. The advantage of this implementation is that there are two data ports per node; one port can be used for addressing, while the other can be used for transmitting sensor data. Under this configuration, power will not be interrupted during addressing. The disadvantage of this implementation is that the power distribution is not very fault-tolerant.

The cable diameter of these implementations can be reasonably small. For example, if the fiber diameter is 250 μm, 100 of them can be packed into a 2.5 mm x 2.5 mm square or a circle with a diameter of 3.6 mm. With the jacket, the cable diameter is probably still less than 5 mm or 0.2". This is roughly only 3 times thicker than a standard single-fiber cable which has a diameter of ~3 mm. A general but not serious drawback of the single-cable implementation of star is that more fibers are used.

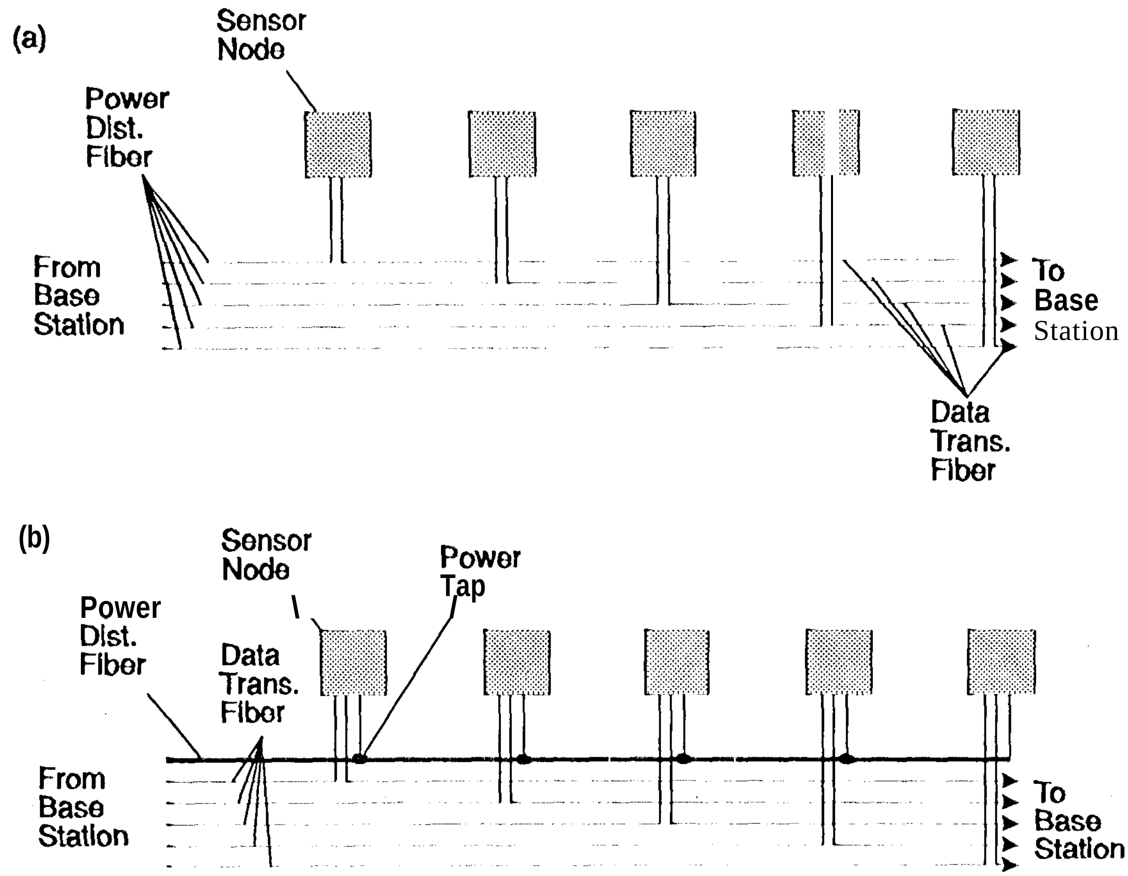


Figure 4 Two examples of the single-cable implementation of star topology.

## OPTICAL-POWER DISTRIBUTION

In implementing daisy-chain topology or hybrid topology, a fundamental issue not found in star topology is how to distribute the power evenly over each node. The most straightforward way, which is the focus of this section, is to use taps or couplers with fixed ratios. To tap equal amount of power at each node, a different tap ratio is needed for each node. The question then is, what is the tap ratio at each node? How are they dependent on other properties of the network? Once the tap ratios are determined, they can be obtained from many vendors as standard products.

If the fibers and connectors are lossless, the answer is fairly straightforward, the tap ratio of nth node from the last node is simply 1/n (see Fig. 5). For example, let us consider a network with 3 nodes only. Then the tap ratios for the last node, second node from the last and third node from the last are 1, 1/2, and 1/3, respectively. This can be verified as follows. By definition, an even power distribution would mean that each node should receive 1/3 of the *total* power. Apparently, the first node *from the laser* (or the third node from the last node) should tap 1/3 of the power off the fiber and pass 2/3 of the power on. The second node from the laser (also from the last node) should tap 1/2 of the power off the fiber, and pass the remaining 1/3 of the total power to the last node. Finally, the last node apparently should tap 100% of the power off the fiber to get its share of 1/3 of the, total power.

This 1/n formula indicates that the tap ratio does not depend on any property of the network. The last node of any network always has a tap ratio of 1 and the nth node from the last node always has a tap ratio of 1/n, in general. What is significant about this fact is that tap ratios need not be recalculated each time a different sensor network is considered. A bonus from this fact is that couplers with standard coupling ratios can be ordered in quantity and hence cost effectively.

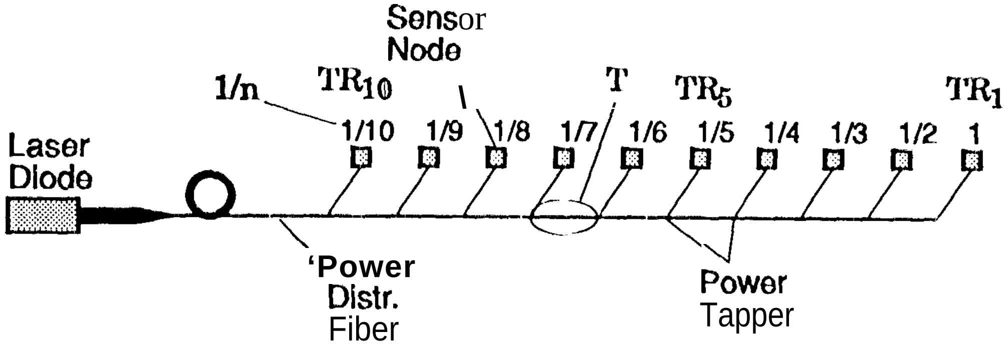


Figure 5 Uniform power distribution in a lossless daisy-chain sensor network
$TR_n$: Tap Ratio at node n from last node; 'T': Internode Transmission (Loss)

Apparently, the 1/n formula does not apply to the case of a lossy link. It can be shown that in the lossy-link case, the *nominal* tap ratio $TR_n$ at the nth node from the last node is given by

$$TR_n = \frac{T^{n-1}}{1 + T + T^2 + \cdots + T^{n-1}} \tag{1}$$

where 'T' is the internode transmission or (1 - Internode Loss). Nominal tap ratio is defined here as the coupling ratio of a coupler without excess loss. Uniform internode losses are assumed here.

If there are no internode losses, i.e. 'T'=1, Eq. (1) indeed reduces to the 1/n formula.

For T≠1, using the relation,

$$1 + T + T^2 + \cdots + T^{n-1} = \frac{1-T^n}{1-T} \tag{2}$$

Eq. (1) can be further reduced to a more compact form,

$$TR_n = T^{n-1}\,\frac{1-T}{1-T^n} \tag{3}$$

To obtain the actual tapped power ratio, the. nominal tapped power at the nth node has to be corrected by the excess loss of the coupler. Namely, if the excess loss is x dB, the actual input power has to be x dB above the nominal tapped power.

As an example, let us assume the excess loss of the coupler is 1 dB, the fiber loss is negligible, and there are 10 nodes totally in the network, Then the internode transmission is T=79%. The nominal percentage of total power distributed to each node, as calculated using n= 10 in Eq. (3), is 2..9% as opposed to the 10% value expected in the lossless-link case. After corrected by the 1-dB excess loss, the power distributed to each node is now only 2.3% of the total power. The overall loss, calculated as 2.3%,/1 0%, is 6.4 dB. The nominal tap ratios for each node counted from the laser are

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| TR = | 2.9% | 3.7% | 4.9% | 6.5% | 8.7% | 12% | 17% | 26% | 44% | 100% |

as opposed to

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| TR = | 10% | 11% | 13% | 14% | 17% | 20% | 25% | 33% | 50% | low, |

in the lossless case. Couplers with a ratio from 1 % to 99% are. available as a standard product from most fiber-optic vendors.

Similar to the l/n formula, Eq. (3) suggests that tap ratios arc independent of the total number of nodes. The tap ratio of the last node is always 1, the second from the last is always 'J'/(l +T), and so on, no matter the total number of nodes. The tap ratio dots depend on the loss of the coupler and fiber. This is not a problem as long as the losses of the coupler and fiber do not vary too much from node to node.

## POWER BUDGET

The power budget of a sensor network depends on the topology used. For star topology, the power budget is about the same for each node and the power budget can be estimated on a per-node basis. For daisy-chain topology, the power budget has to be considered by treating the network as a whole, because the total loss seen by each node is different. In the following, the power budget per node for a star network is first estimated. Then the power budgets for 10- and 100-node star sensor networks arc compared to those of daisy chain sensor networks.

In optically-powered ac electric and magnetic field sensors developed previously at JPL,[4,5] the hybrid circuit required about 275 μW and was supplied by a 50 mW semiconductor laser diode, About a third of the power was consumed by an op-amp chip used to handle the analog signal from the sensor. Another third was consumed by the LED used to return a coded optical signal to the base station. The op amp was a low power commercial chip, drawing 100 μW. The LED was also estimated to require 100 μW on average.

The micro-sensor node should be designed to reduce the total node chip power by a factor of 10 or 20, to about 10 to 20 μW. A power budget for the optical power source can be estimate.d as shown in Table 3, assuming a node chip requires 20μW, and with conservative estimates of 1o sscs.

Based on Table 3, 10 node and 100-node star sensor networks would require a total laser power of 1 S dBm (31.6 mW), and 25 dBm (316 row), respectively.

For daisy-chain topology, the laser power required can be calculated by considering the first node from the laser, The power that reaches the first node of an N-node daisy-chain network is given by

$$p = P_{LD} \cdot TR_N \cdot T_{exc} \cdot T_{OTHER} \tag{4}$$

where 1'1,1, is the power of the laser diode., $TR_N$ is the nominal power tap ratio for the first node from the laser (or Nth node from the last node), $T_{exc}$ is the excess loss Of the coupler in linear scale as oppose to dB, and $T_{OTHER}$ is the overall loss in Table 3 in linear scale.

**TABLE 3 Power Budget Per Node for Star Topology**

| PARAMETER | F |
|---|---|
| Node chip power required | -17 dBm (20 μW) |
| Laser coupling loss | 3 dB (0.5) |
| Fiber length loss, (1 km) | 6 dB (0.25) |
| Photodiode 1oss (optical to electrical) | 10 dB (0.1) |
| Laser duty cycle: | 3dB (0.5) |
| overall loss: | 22 dB (0.00631) |
| Laser power required = Node chip power required + Overall loss | 5 dBm (3.16 mW) |

Substituting Eq. (3) into Eq. (4) with some manipulation yields the required laser power for a daisy-chain network

$$P_{LD} = \frac{P}{\eta_{OTHER} T_{exc}} \cdot \frac{1-T^{N}}{T^{N-1}(1-T)} \qquad (5)$$

$P/\eta_{OTHER}$ is actually given by the laser power required listed in Table 3. To compare the laser power required for daisy-chain networks, let us assume the excess loss of the power tap is 0.5 dB on average and the fiber loss is negligible. Then based on Eq. (5), the laser power required for 10 node and 100 node networks are 18 dBm (63.1 mW) and 64.6 dBm (2.88 kW!), respectively. The fact that the difference between 10 node and 100 node is almost 4 order of magnitude indicates that the power requirement for a daisy-chain network grows extremely nonlinearly with the number of nodes.

From the analysis performed above, star networks are clearly more energy-efficient than daisy-chain networks. Also, this analysis can be used to determine what number of nodes in a branch of a hybrid network is adequate. From the example above, that number probably should be less than 10. Although the analysis performed above is for power distribution, similar power requirements is also expected for data transmission.

## SUMMARY AND CONCLUSIONS

We have discussed an all-fiber sensor network regarding its properties, topologies, tradeoffs, power budget, and potential applications. The tradeoff analysis shows that the star topology, in particular the single-cable implementation, is the most favored topology with the only disadvantage of requiring more fibers. The daisy-chain topology is not favored in all categories except in number of fibers needed and installation handling (which is also favored by the single-cable implementation of star topology). The hybrid topology, which is a mixture of these two and more favored than the daisy-chain, may still be valuable in certain applications in which number of fibers used must be reduced to be less than required by a star topology. Power budget estimate indicates that a daisy-chain network consumes much more power than a star network. All-fiber sensor networks are required in certain applications in which EMI immunity and/or corrosion resistance are necessary. In general, an all-fiber sensor network is more reliable, compact, and light-weight than its copper-wire counterpart, with the only disadvantage of costing more for the time being. Nevertheless, the cost of an all-fiber sensor network is expected to come down significantly soon, since the market of other fiber and laser-diode based applications such as cable TV networks and CD-ROM are growing rapidly.

## ACKNOWLEDGMENTS

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